A Neptune Orbiter Mission

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Abstract

This Paper describes the results of new analyses and mission/system designs for a low cost Neptune Orbiter mission. Science and measurement objectives, instrumentation, and mission/system design options are described and reflect an aggressive approach to the application of new advanced technologies expected to be available and developed over the next five to ten years. The application of these new technologies have both reduced costs and increased science return compared to previous designs.

1. Introduction

Over the past two years a focused effort has taken place to define new low cost missions to explore the Neptune system. The Voyager mission on its flyby past Neptune in 1989 returned fascinating information about this complex system that includes the gas giant planet, its large moon, Triton, other satellites, and a system of rings, ring arcs, and shepherding satellites. This paper describes the results of effort to design low cost orbiter missions that will allow time to explore all aspects of the rich treasure of scientific information that the Neptune system holds.

Past design studies of Neptune Orbiter missions, as early as the 1970s, had resulted in relatively expensive missions (> $800 M in today's accounting dollars) with long flight times (> 15 years) to reach Neptune. Projected technology advances hold the promise of significantly reducing the launch mass, flight time, and cost. What we have already learned about the Neptune system allows us to set science and measurement objectives, leading to instrumentation possibilities and strategies for operating the spacecraft. Technology advances and the mission/system designs that are then possible with their application are described. Our information base on the Neptune system is small enough that the primary mission objective will be exploration.

2. Science and Measurement Objectives

NASA's Office of Space Science, via the Solar System Exploration Roadmap (SSER, see Reference 1), and its advisory group, the Astrophysical Analogs in the Solar System Campaign Science Working Group (AACSWG, chaired by W. B. Hubbard) provided guidance concerning the science goals motivating a Neptune Orbiter mission. Relative to the SSER's priorities, the Neptune Orbiter mission attempts to explore (1) the atmospheric structure and circulation at Neptune and Triton, (2) ring particle physical properties, dynamics, and distribution, (3) magnetosphere structure and dynamics, (4) the Neptune gravity field, and (5) the composition, structure, and activity of Triton's surface. These address directly the SSER goals of understanding the origin of the solar system and the objects within it, and understanding the processes now occurring in planets, and how they are evolving. The AACSWG also sees the exploration of the Neptune system as a means of understanding the evolution and dynamics of other solar systems and their planetary systems.

Neptune Orbiter mission science goals are manifested in three high-priority science objectives for Neptune, and three for Triton. The high-priority Neptune science objectives are:

1. Study of Neptune's system of rings, ring arcs, and shepherd satellites over an extended time period, at least two terrestrial years
2. Long-term monitoring and study of Neptune's dynamic atmosphere
3. Extended temporal and spatial sampling of Neptune's magnetosphere

The high-priority Triton science objectives are:
1. Mapping of Triton's surface features
2. Monitoring and study of Triton's nitrogen-rich atmosphere
3. Monitoring of Triton's seasonal cycles

Monitoring and study of Neptune's and Triton's atmospheres include measurements addressing both dynamics and composition, within the capability of remote sensing instruments. Definitive spectral data from remote sensing instruments is unfortunately limited to relatively shallow levels in Neptune's atmosphere, to a few bars at most. Radio astronomical methods can probe deeper levels, but such information's resolution is extremely limited and its interpretation is ambiguous. Gaining accurate, unambiguous knowledge of Neptune's bulk composition will probably require deep atmospheric entry probes, possibly derivatives from prior jovian entry probe designs. Entry probe missions are beyond the scope of this orbiter mission and are not treated here.

Measurement suites that would provide the data set needed to achieve these objectives are not yet fully defined. In the absence of definitive measurement requirements, the AACSWG recommended a preliminary instrument list to use during these initial design studies and gave general guidelines concerning image resolutions, etc. For example, they recommend images of Neptune's ring system with spatial resolution of about one km.

3. Instrumentation

The AACSWG recommended a suite of eight dedicated science instruments for the Neptune Orbiter payload. These are listed in Table 1 below, along with typical measurements to be made by those instruments. The first three would likely be integrated into a single instrument package, possibly sharing optics as demonstrated by the PICS and MICAS instruments now under development. An instrument to fly on the Neptune Orbiter mission would be a next-generation successor to those instruments, with smaller resource demands and possibly better performance. The last four instruments, all fields and particles instruments, would also likely be integrated into a single instrument package, possibly a successor to the ISPI instrument under study at JPL.

Instrument	Typical Measurements Performed
Visible Imager	Neptune atmospheric imaging; Ring system & satellite imaging; Triton surface mapping, geyser monitoring
IR Imaging Spectrometer	Neptune atmosphere, ring, & Triton surface imaging, yielding compositional information
UV Imaging Spectrometer	Neptune & Triton upper atmospheric imaging, yielding compositional information
Thermal IR Spectrometer	Neptune atmosphere, ring, & Triton surface temperature measurements
Magnetometer	Magnetic field strength & direction; solar wind/ magnetosphere interactions
Ion & Neutral Mass Spectrometer	Compositional information on Neptune's magnetosphere and Neptune and Triton's exospheres
Charged Particle Detector	Solar wind and magnetospheric particles, and their interactions
Plasma Wave Spectrometer	Magnetospheric waves; diagnostic information about solar wind/magnetosphere interactions

Table 1. Preliminary instrument complement recommended by the AACSWG, and typical measurements performed by those instruments.

In addition to the dedicated science instruments listed above, Radio Science investigations are possible using a spacecraft radio telecommunications system, if its capabilities allow. Use of an optical, rather than radio, primary telecommunications system is one option considered for the Neptune Orbiter mission. In that case, a backup radio system may not have sufficient SNR for worthwhile Radio Science investigations. But if the primary telecommunications system uses radio wavelengths, or if a backup radio system has sufficient SNR, then addition of an Ultrastable

Oscillator (USO) to the telecommunications system enables a variety of high-value occultation and Doppler tracking investigations with little impact on spacecraft resources. If sufficient priority is given to such investigations, it will be worthwhile to examine uplink radio occultation experiments for inclusion on the mission. Uplink experiments have greater impact on spacecraft resources due to onboard computation requirements, but the science return is greatly enhanced over standard downlink experiments.

Mission requirements arising from Neptune's great distance from the Sun and Earth place rather strict constraints on the payload's mass, power consumption, and telemetered data rate. In all cases use of existing instruments would violate the constraints, so a significant instrument development effort is assumed. Studies to date use instrument mass and power figures that are allocated rather than estimated, so they represent goals for the development programs. The current spacecraft design allocates 8 kg and 12 Watts to the instrument payload. Instrument data rates, especially for the imaging instruments, require high data compression ratios to fit practical telemetry rates.

4. Autonomous Operations

Autonomous science operations have been suggested as an approach to easing the data return problem. Such operations would not usually return raw or even highly compressed imaging data, but instead would return high-level interpretations of imaging data, such as derived wind fields, atmospheric feature drift rates, etc. Alternatively, or additionally, autonomous spacecraft control algorithms might recognize certain phenomena from data taken, allocating further data acquisition, reduction, and return based on predetermined priorities. Since data reduction and the first steps of data interpretation would be performed on the spacecraft, downlink of the resulting knowledge would require many fewer bits than downlinking even highly compressed raw data.

But autonomous science operations might have limited utility until late in the mission, mainly due to the state of Neptune science before this mission arrives. Neptune's distance from Earth and the Sun currently places Neptune science in a very different position from Jupiter science, for example. Three hundred years of telescopic studies of Jupiter, the last hundred of them at reasonably high resolution and the last eight benefiting from the Hubbell Space Telescope (HST), close flybys by five spacecraft (Pioneers 10 & 11, Voyagers 1 & 2, and Ulysses), and detailed exploration by the Galileo orbiter and atmospheric entry probe, combine to yield a knowledge base for Jupiter unparalleled among the gas giant planets. The planetary science community would not be too uncomfortable with a Jupiter probe that monitored known atmospheric phenomena and sent back high-level results, especially when those results could initiate intense and worthwhile study by Earth-based telescopes and HST. On the other hand, before HST Neptune was only a few pixels in even the best of Earth-based telescopes. Our knowledge of Neptune was limited almost entirely to low resolution spectroscopic data; Neptune's atmospheric dynamics were essentially unknown. HST resolution of Neptune is only equivalent to Earth-based telescopic resolution of Jupiter. In terms of pixels per planetary diameter, it is far worse. And we have data from only a single spacecraft encounter with Neptune, Voyager 2 in 1989. Indeed we gained a wealth of new information from that encounter, but it was a snapshot of Neptune's state at the time. Since then, HST data indicate that the Great Dark Spot Voyager 2 saw in Neptune's southern hemisphere disappeared, and another albedo feature has appeared in Neptune's northern hemisphere. Is it another Great Dark Spot? Or is it a new phenomenon, unseen by Voyager 2? No one knows. With our knowledge of Neptune's atmosphere in such a state, the planetary science community is unlikely to support a Neptune mission that depends entirely on autonomous data reduction and initial interpretation based on pre-arrival knowledge.

Triton is in a similar situation. Even HST sees Triton as a single pixel. Due to its obliquity, Voyager 2 saw only half of it, and that half showed a great variety of features. Notably, different regions within the illuminated hemisphere had features not seen in other regions. No one would suggest that characterizations of one region's features are sufficient also to characterize the other regions' features. Likewise, no one would suggest that characterizations of the features Voyager 2 saw will be sufficient to describe the features to be seen on the other half of Triton.

This problem motivated dividing the mission at the planet into two phases, a "characterization" phase, and a "monitoring" phase. The characterization phase aims at mapping Triton's unseen hemisphere and determining Neptune's state upon arrival, with an observation strategy independent of previously observed phenomena and a data return strategy emphasizing high compression ratios to return raw data. This minimizes the likelihood of new phenomena being overlooked by inappropriate (due to insufficient knowledge) autonomous interpretation algorithms. When the science team is satisfied that our knowledge about Neptune or Triton has progressed to the point that "trustable" algorithms can be written, those can be uplinked to the spacecraft and the monitoring phase for that target begins. Of course, those algorithms must contain means for reverting to raw data return upon detecting any pattern that does not fit their recognition algorithms, or upon receiving a command from ground controllers. The autonomous operations phase, or monitoring phase, will most likely be a requirement if we are to limit operations cost and return the enormous amount of information that is believed needed to understand this complex planetary system.

5. Technology Advances and Mission/System Design Options

Neptune Orbiter has been an elusive mission/systems design goal for many years. Flight times as high as 20 years were suggested in designs of the 1980s. Later designs of the early 1990s took advantage of miniaturization technologies of the times and reduced flight times to a little over 16 years. Price tags of these later designs were as low as $650 M, in FY98 $ (Reference 2). Current design studies hold out the potential for flight times of 10 years or less and price tags approaching the top end of a Discovery mission, $250 M to $350 M, in FY98 $. These attractive features, low cost and relatively low flight time, are made possible by the application of advances in technology available in the next 5 to 10 years.

5.1 Preliminary Key Technology Needs

An enabling technology for the low cost Neptune Orbiter is the means to aerocapture into Neptune orbit without the expense of launching large amounts of chemical propellant. Aerocapture takes advantage of the drag afforded by the top of Neptune's atmosphere to slow the spacecraft's approach velocity enough to achieve orbit insertion. Navigation, thermal control, and flight path control are all parts of the development of aerocapture technology. Neptune entry speeds near 30 km/s region drive the thermal and flight path control. The sensitivity of spacecraft system mass to increases in entry speed is less for aerocapture than for chemical propulsion. Aerocapture technology enables the higher entry speeds and thus the lower flight times of interest, 10 years or less. Aerocapture development is already in process for planetary missions. The Mars Surveyor Program plans to use it for all their future orbiter missions. Venus, Titan, and the Outer Planets are targets for application of aerocapture technology. Aggressive technology development will be needed for the Neptune Orbiter missions planned, because low aerocapture system mass ratios will be needed, on the order of 25% to 35%.

The Advanced NSTAR Solar Electric Propulsion System is an enabling complement to aerocapture technology in achieving delivery of a system that can support the kind of science needed for exploration. This system appears particularly capable for the desired flight times and lower-cost launch vehicles. An attractive feature of low thrust propulsion is its launch opportunity flexibility. For example, it would be possible to launch a mission almost any year, instead of waiting for Jupiter gravity-assist opportunities every 12 to 14 years.

Operating a spacecraft at Neptune without a nuclear power source is extremely difficult. Inflatable solar collectors must be large to collect enough sunlight to support the spacecraft in Neptune orbit; one estimate is over 20 m in diameter. This large solar array would have to be deployable after the aerocapture. Early technology development appears promising for applications closer to the Sun. If flight demonstrations and mission applications are successful, then an evolving application to the Neptune Orbiter mission/system design is a possibility. Radioactive power sources currently appear as simpler developments and application to the Neptune Orbiter system design. In particular, a 12.5 W/kg rated AMTEC 3-GPHS fresh-brick design appears a highly efficient choice for the low cost approaches taken in the mission studies performed. Given a 10-year flight time and 2-year on-orbit mission, 166 W would be available after 12 years. The potential risk of applying this technology is achieving success in the launch approval process.

Optical communication is potentially enabling for the Neptune Orbiter mission. Exploration of such a complex system needs as many bits of information as possible returned. Continuing trade studies are needed with both technologists and scientists participating to evaluate the promise that optical communication holds for the Neptune Orbiter mission.

The Neptune Orbiter designs yielding lower costs and lower flight times aggressively apply micro-technology systems to all spacecraft systems and instruments. Development of these types of systems is a high priority for all of NASA's advanced missions and has a deserved high priority in NASA's technology investment plans. To reach the level of mass reduction desired for the mission/system designs we may have to wait five to ten years before we can insert these developments into flight projects. This would imply application launches 8 to 13 years from today, including the additional 3 years after technology readiness for integration into the flight project design.

Table 2 summarizes the key technology needs for a low-cost, low-flight-time Neptune Orbiter mission.

Technology	Concerns	Impacts
- Ballute Aerocapture	ΔV for chemical propulsion orbit insertion very high for TF < 12 yrs; drives launch mass/TF	Enabling; Aerocapture system mass ratio of 25% to 35% - requires aggressive technology development *($20+ M in Development)*
- Advanced NSTAR Solar Electric Propulsion	Delivery of sufficient science mass to Neptune; drives launch mass/TF	Enabling for Desired Science; *(~ $20 M Development)*
- Advanced Radioactive Power Source (RPS)	Long Life Mission/Operation at Neptune; Nuclear Power Source	Enabling - AMTEC: 12.5 W/kg - 166 W at 12 yrs *($25 M Development);* Launch Approval Process
- Optical Communication	High data rate desired; drives power mass/TF	Potentially enabling; development and cost definition in process *($10 to $20 M Development)*
- General μ-Tech. Systems/Instruments *(Cross-cutting Tech.)*	Some Break-Through Development Required/Expected; High Cost & Schedule Risk for Launch < 2006	Launch > 2006 *(Dev. Proceeding; e.g., NASA X2000 & Core Technology Programs)*

Table 2. Preliminary Key Technology Needs Summary

5.2 Neptune Orbit

A combination of different orbits about Neptune allow efficient gathering of the exploration data. The sequence of orbits is made possible by a combination of propulsive maneuvers and close Triton flybys. Because Triton's orbit is inclined by 157°, aerocapture is retrograde and provides polar visibility, out-of-plane ring views, and Triton flybys. After aerocapture a periapsis-raise maneuver places the spacecraft in a 150-day orbit. Subsequent maneuvers reduce the orbital period to 12, 6 , and 3 day orbits. This sequence allows observations of Neptune's atmosphere, rings, and magnetosphere, and Triton.

5.2 Mission/System Design Technology Options

Because advanced technologies are so important to implementation of a low cost Neptune Orbiter mission, a series of design studies to evaluate their impacts was carried out, starting in January 1997 and ending in November 1997. From these studies a baseline mission/system was established and two aggressive technology variations were compared and costed. The first variation entails a highly integrated spacecraft of micro-technology systems, termed Second Generation Spacecraft. The second variation applied inflatable technology for both power and telecommunications. All three options assumed launch after 2006 on a Delta II 7925H launch vehicle, aerocapture, and two years of Neptune orbit operations.

The baseline design aggressively applied micro-spacecraft technology. A spacecraft wet mass of 170 kg was achieved, including aerocapture system and propulsion required for on-orbit operations. The baseline design also includes a 950-kg Advanced NSTAR Solar Electric Propulsion system to achieve the desired transfer orbit energy and delivery of the spacecraft to Neptune in 10 years. The NSTAR system is not needed after reaching 3 AU, so the AMTEC power system supplies power from then on. The desired science is supplied by an advanced 7.5-kg integrated instrument package, including measurements for all eight of the required investigations described in Section 3. Total baseline mission cost estimate is $310 M.

An over-the-horizon technology analysis and development effort at JPL is designing a highly integrated spacecraft that has the potential to enable low cost missions to anywhere in our solar system. This design goal is achieved by reducing spacecraft mass to such a degree that low cost launch vehicles can be used without loss of science return. The Second Generation Spacecraft approach provided a wet spacecraft design of 37 kg. Cost and flight time are reduced from the baseline design by substituting a Star 30 solid rocket upper stage for the Advanced NSTAR SEP system. Flight time is reduced by 1.5 years to 8.5 years, and cost is reduced to about $250 M. However, the Second Generation Spacecraft approach yields a Neptune Orbiter design with a major problem: an unacceptable reduction in science return. The 5.5-kg instrument package was unable to return data of sufficient quantity or resolution for the eight science investigations described in Section 3. A new advanced, highly integrated spacecraft design, geared to outer planet orbiters, might have potential for cost and flight time reductions over the baseline design, and still provide the required science.

Another technology option is the use of an inflatable array to supply solar power and act as a communications antenna. The baseline design is unchanged except for the integration of an all-solar power option, deleting the AMTEC power system. The mass impact is significant, resulting in a negative launch vehicle margin: -17%. An Atlas IIARS launch vehicle would provide more than enough margin, but the mission cost would increase by about $40 M.

Table 3 below summarizes the options detailed above.

Implementation Option	Flight Time to Neptune	Science Payload	Mission Cost	Comments
• Adv. μ-Tech S/C & Instruments (Delta 7925H + Adv. NSTAR/SEP)	10 yrs	Desired Science; 7.5 kg	$310 M	A Baseline mission/system design solution
• 2nd Generation S/C - Very Aggressive μ-Tech Systems Development (Delta 7925H/Star 30BP)	9 yrs	Reduced/ Unacceptable Science; 5.5 kg	$250 M	The given μ-Tech systems resulted in reduced/ unacceptable science
• Inflatable Technology for Power & Telecommunications Adv. μ-Tech S/C & Instruments (Delta 7925H + Adv. NSTAR/SEP)	10 yrs	Desired Science; 7.5 kg	$350 M	The system design solution is too massive with the given Inflatable technology for the Delta II; add ~ $40 M for Atlas IIARS

Table 3. Comparison of Mission/System Design Technology Options (Launch > 2006; Aerocapture; 2 yrs of On-Orbit Operations)

6. Conclusions

Although the exploration science goals for a Neptune Orbiter mission are available, additional interaction between the mission/system designers and the science community is needed to understand the trades between science return, cost, and technology requirements - particularly in the area of autonomous operations during Neptune orbit.

The key to a low-cost Neptune Orbiter mission is the development of advanced technologies - aerocapture, Advanced NSTAR Solar Electric Propulsion, optical communications, an advanced radioactive power source, and micro-technology systems and instruments. All of these are currently in development to some degree, but will need an aggressive approach if they are to be ready in the next 5 to 10 years.

The Second Generation Spacecraft Systems Design shows great promise, but will need further refinement for application to the very difficult Neptune Orbiter mission/system design challenge. Likewise, inflatable solar array technology is a solution to the all-solar power requirement, but is not yet mass or cost efficient enough to replace the radioactive power source solution.

Neptune Orbiter remains an important Solar System Exploration Strategic Plan objective. With focused advances in key technologies, this mission can be low cost and have reasonable mission durations.

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8. References

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